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AUTONOMOUS CONTROL SYSTEM FOR CZOCHRALSKI GROWTH OF LEC GaAs

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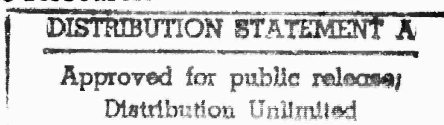
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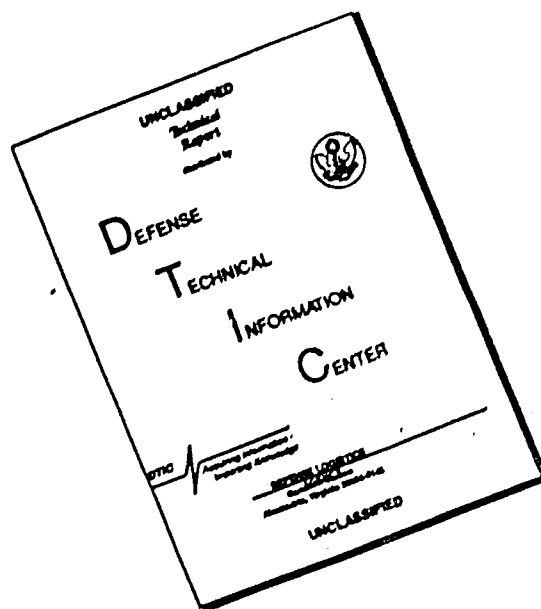
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During the first period (1 year) this system has grown 30 single GaAs crystals with a yield of better than 70% of single crystals. (Keywords:

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AUTONOMOUS CONTROL SYSTEM FOR CZOCHRALSKI GROWTH OF LEC GaAs

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ABSTRACT

This program reports research done under DARPA contract number F49620-86-C-0012. The goals of this program include the establishment of autonomous LEC crystal growth and its commercialization. This report provides a short description of the autonomous control system, a detailed description of the digital hardware developed for the control system and the multibus computer system and the computer-puller hardware of the growth system. Technical drawings for the signal processing box and the motor controller board are also given.

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SUMMARY

This report provides a short description of the following subjects:

* a short description of the autonomous control system developed for single crystal growth of GaAs. (For details see report entitled Autonomous Liquid Encapsulated Czochralski (LEC) Growth of Single Crystal GaAs by "Intelligent" Digital Control).

* a detailed description of the digital hardware developed for the above system.

* the multibus computer system and the computer-puller hardware of the growth system.

Technical drawings for the signal processing box and the motor controller board are also given.

During the first period (1 year) this system has grown 30 single GaAs crystals with a yield of better than 70% of single crystals.

1. INTRODUCTION

The Czochralski Growth Control System (CGCS) consists of a Cambridge Instruments 358 high-pressure puller controlled by a digital computer for growth of single-crystal gallium arsenide by the Liquid Encapsulated Czochralski (LEC) method. The digital controller, developed at Arizona State University's Semiconductor Materials Research Laboratory under sponsorship of DARPA, replaces the standard analog controller supplied with the puller.

Digital control of crystal growth provides several advantages:

- Greater flexibility and increased sophistication of control methods.
- Better reproducibility of growth process parameters and control actions.
- Expanded data presentation to the operator and data logging.

Physically, the CGCS comprises three main parts shown in Figure 1: the Cambridge Instruments puller and two systems for controlling the puller, the Cambridge.Instruments analog console, and the ASU digital console, which is based on an Intel 8085 microcomputer. A switch, set by the digital console, determines whether the analog or digital console controls the puller.

This report gives an overview of the operation of the system as well as descriptions of hardware and software of the digital controller.

2. SYSTEM DESCRIPTION

The digital controller of the CGCS operates in several modes, which range from monitoring the growth process as it is controlled by the Cambridge analog console, to taking full automatic control of crystal growth with minimal interaction required by an operator. Details of these operating modes are given in reports listed in references 1 and 2. In these reports operation in the fully automatic mode is briefly described, as this is the mode that is unique to the CGCS and most powerful for crystal growth. A familiarity with LEC growth of gallium arsenide is assumed.

Figure 2 is a diagram of the puller, including the electronic balance that provides a continuous measurement of crystal weight, which is used to calculate the crystal diameter. A simplified view of the digital control system, utilizing a combination of feedforward and feedback, is shown in Figure 3. Omitted from the diagram are analog anti-aliasing filters, A/D and D/A converters, and some digital filtering of signals received from the puller.

Also absent are control loops for lift and rotation of the seed and the rotation of the crucible, which are largely independent of the rest of the controller structure. The components to the left of the dashed line are implemented in software. The blocks labeled "PID" are digital proportional-integral-derivative controllers implemented by a single subroutine.

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Automatic diameter control is effected by changing the heater temperature setpoint T_S, which is the sum of a bias temperature T_B and the output of the diameter PID controller. The bias temperature consists of a component T_{BO}, which represents the a priori knowledge of the temperature setpoint required to grow a crystal, and a correction term dT_B, which is generated during the growth. Normally, the diameter PID controller provides the necessary augmentation of T_{BO}; however if the system detects a large diameter error, an additional temperature correction dT_B is automatically generated by the control software.

A steady growth rate is maintained by keeping the seed lift speed constant and lifting the crucible so as to maintain a constant height of the liquid-melt interface as the melt is depleted from the crucible. This is accomplished via the crucible lift speed setpoint Z_S, which is the sum of a bias speed Z_B and the output of the crucible position PID controller. The bias speed consists of an a priori term Z_{BO} and a correction term dZ_B that is generated if the system detects that the crucible position PID controller is unable to augment Z_{BO} sufficiently to maintain the growth rate within a specified range.

The "ESTIMATION ALGORITHM" block represents a subroutine that performs two main functions: estimation of the current diameter and computation of a setpoint for the crucible height. Diameter is estimated from the differential weight measurement dW/dt and several other measurements indicated by Y. This algorithm accounts for the buoyancy force of the boric oxide encapsulation by storing the shape of the crystal already grown. This PID controller algorithm and the estimation algorithm are fully described in the report entitled Digital Control of the Czochralski Growth of Gallium Arsenide - Operator's Manual.

3.   CGCS HARDWARE - FUNCTIONAL DESCRIPTION

The ASU digital console is shown in more detail in Figure 4. The components of this system, which communicate via the Intel Multibus*. can be conceptually grouped as shown by the dashed lines. Names underscored int his section indicate components in Figure 4.

The center of operations is the Processor and Memory section. The CPU (central processing unit) is an Intel Single Board Computer, including an 8085 microprocessor, 16 KBytes of read-only memory, 8 KBytes of random access memory, and an arithmetic processor to speed numerical calculations. The Memory Expansion board provides an additional 48 KBytes of random access memory. The Disk Controller manages two Flexible Disk Drives. One drive stores programs that are loaded into the random access memory for execution, while the other stores crystal growth data for offline analysis following the run.

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*"Multibus", "ISIS" and "iRMX" are Intel Corporation trademarks.

The Analog Input section accepts analog data from the puller for transfer to the digital processor. The following analog sources are monitored:

- Three thermocouples that measure the three heater-zone temperatures. (The system currently includes only one heater, although present software provides for independent control of three heaters.)
- Three wattmeters connected to the puller heaters.
- Four tachometers that measure the motor speeds for lift and rotation of the seed and the crucible.
- Two potentiometers that monitor the seed lift and crucible lift positions.
- The crystal weight gauge.
- An analog differentiator that provides a filtered time derivative of the weight gauge signal.
- A gauge that senses gas pressure inside the puller.
- A contact device that indicates contact between the seed and the boric oxide or between the seed and the GaAs melt.
- Eight spare channels that can be used to monitor supplementary devices.

The analog signals are passed through Isolation amplifiers to provide preamplification of the analog signals and to separate the analog from the digital circuitry. A low-pass Filter removes high-frequency components that would otherwise corrupt (alias) the sampled signals. The analog signals are then multiplexed and fed to a 16-bit A/D converter which makes the digitized data available to the CPU via the Multibus.

The Analog and Digital Output section takes signals from the CPU via the Multibus and sends them to the puller or to a Printer and a Pen Recorder in the Operator Interface section. The D/A converter accepts 12-bit digital signals and converts them to analog equivalents. These signals are:

- Three heater SCR control voltages.
- Four voltages to control the speeds of motors for lift and rotation of the seed and crucible.
- Eight signals routed to the Pen Recorder for monitoring important crystal growth signals.

Digital output signals are fed through the I/O Expansion board to the Relay Board. One relay determines whether the digital console or the analog console controls the four motors that lift and rotate the seed and the crucible. If the digital console is in control, the other relays determine whether a motor is stopped, directed clockwise, or directed counterclockwise.

The Operator Interface section provides for communication between the user and the digital console via the CRT Terminal, the Printer, and the 8-channel Pen Recorder. The operator

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monitors the status of the crystal growth from data automatically written to the CRT screen and commands the system through the keyboard. The line printer periodically records the crystal growth data, and also copies the operator-system dialog from the CRT Terminal. This provides a record of events for reference during and after the crystal growth. The Pen Recorder provides continuous graphical output of system variables such as heater temperature and crystal diameter that are important for monitoring the growth and for analysis following the run.

4. CGCS HARDWARE - TECHNICAL DESCRIPTION

A drawing of the physical layout of the ASU digital console is shown in Figure 5, and Figure 6 shows a system block diagram. The following paragraphs describe the system components.

a) Multibus Computer System

The Multibus Computer System is an Intel 8085-based microcomputer built from OEM (original equipment manufacturer) components supplied mostly by Intel. The component boards are connected via Intel's Multibus. The CPU consists of a Single Board Computer (iSBC 80-24) that holds the 8085 CPU, an 8-bit processor than can address up to 64 KBytes of memory. The 8085 is enhanced by an arithmetic processor (9231 chip on iSBX 331 board) that speeds fixed and floating point computations. The Single Board Computer includes 2 x 8 KBytes of ROM and 8 KBytes of RAM. An additional 64 KBytes of RAM is provided by a Memory Expansion board (iSBC 064A). Disk storage is provided by two 8-inch, single side, single density Flexible Disk Drives that are interfaced to the Multibus by a flexible Disk Controller (iSBC 204). Each disk can store 250 KBytes.

Analog data are brought to the processor through a Data Translator A/D converter (DT772/5716-32DI-B-PGH) with 32 differential input channels and a resolution of 16 bits. Data are sent from the processor to analog instruments through a Burr-Brown D/A converter (MP8316-V) with 16 channels and 12-bit resolution for $\pm$10-volt analog outputs. Digital I/O lines are provided by the I/O Expansion board (iSBC 517).

The operator communicates with the system through a "dumb" CRT Terminal (Wyse WY-50) connected to the CPU through an RS-232 serial interface. Hard copy of the operator-system dialog and growth data are provided by a line printer (Itoh 1550) interfaced through the digital I/O Expansion board.

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b) Computer-Puller Hardware Interface

The computer-puller hardware interface consists of a Signal Processing Box (Figure 5) that prepares analog data inputs for the D/A converter, and a Relay Control Panel that activates relays for control of motor directions.

The Signal Processing Box is a rack containing four printed circuit boards. Three boards (Figures 7-9) contain circuitry to condition the analog input signals. The fourth board is a connector board (with no electronic components) that provides connectors for a pen recorder and test points for troubleshooting the electronics. The three signal conditioning boards handle signals indicating:

- base temperature ("thermo-couple B")
- crucible position
- crucible lift and rotation speed
- seed lift and rotation speed ("crystal pull speed" and "crystal rotation speed")
- seed position ("crystal length")
- heater temperature ("thermocouple A")
- crystal weight time derivative ("diff weight")
- crystal weight
- crystal-melt contact
- heater power
- gas pressure

The four speed signals are first divided down to reduce signal levels. Low-pass filters remove high-frequency signal components to prevent aliasing in the A/D sampling process. The signals are then fed to isolation amplifiers (ten Intronics 1A175's and two Analog Devices 285U's for the thermocouple inputs) that preamplify the signals and prevent ground loops that could induce noise. The isolation amplifier oscillators (except for the thermocouple amps) are synchronized by a 555 timer (Figure 9). The amplifier differential outputs are routed to the A/D converter located in the Multibus Computer System.

A schematic of the Relay Control Panel is shown in Figure 10. One relay (K9) determines whether motor directions are controlled by the analog or the digital console. A set of digital logic signals drives relays that control the directions of the four motors for lift and rotation of the seed and crucible. Another set of logic signals that sense the relay states is connected to the Multibus Computer system through its iSBC 5.7 I/O expansion board. In the power-off mode, the motors are stopped. In the power-on mode the motors can be commanded clockwise, counter-clockwise, or stopped. The relay signals at the other side of the schematic are routed to the Cambridge analog console. This relay system provides absolute isolation between the circuitry of the puller and the computer.

5. REFERENCES.

1. Digital Control of the Czochralski Growth of Gallium Arsenide - Controller Software Reference Manual; published July 15, 1987; scientific report, October 1, 1985 - March 31, 1987.

2. Digital Control of the Czochralski Growth of Gallium Arsenide - Short Reference Manual; published August 10, 1987; scientific report, October 1, 1985 - March 31, 1987.

3. Digital Control of the Czochralski Growth of Gallium Arsenide - Operator's Manual; published August 3, 1987; scientific report, October 1, 1985 - March 31, 1987.

4. Autonomous Liquid Encapsulated Czochralski (LEC) Growth of Single Crystal GaAs by "Intelligent" Digital Control; published August 19, 1987; scientific report, April 1, 1987 - September 30, 1987.

5. Digital Control of LEC Gallium Arsenide Crystal Growth; published September 21, 1987; scientific report, April 1, 1987 - September 30, 1987.

6. Interactive Digitally Controlled GaAs LEC Crystal Growth; published November 16, 1987; final report.

7. Analog and Digital Growth of LEC Gallium-Arsenide Single Crystal; published August 25, 1987; scientific report, October 1, 1984 - March 31, 1987.
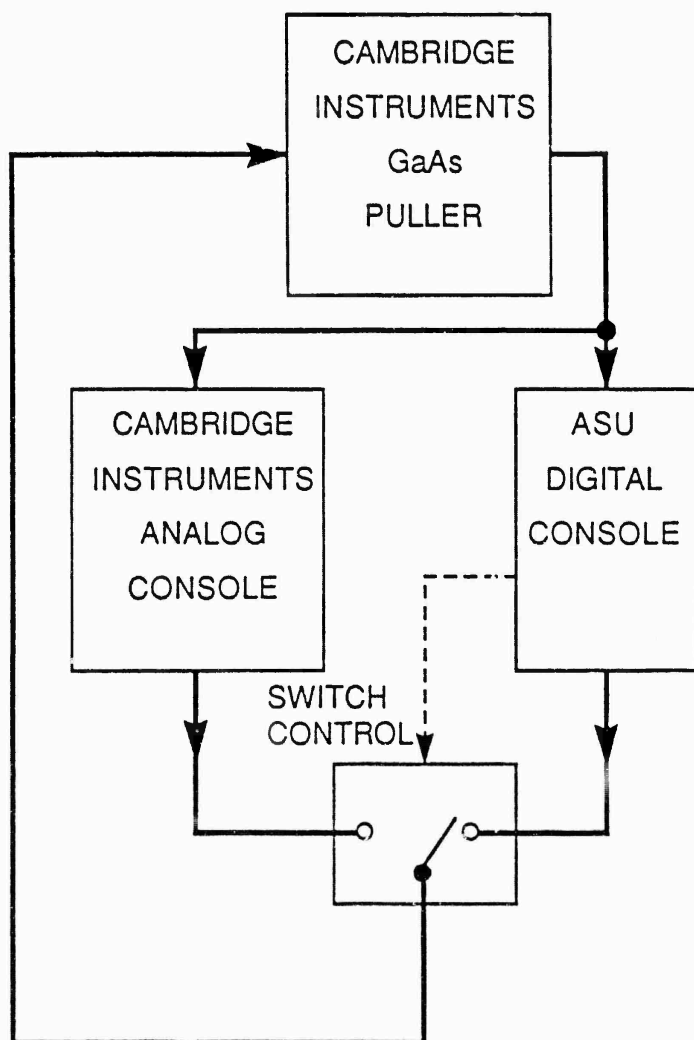
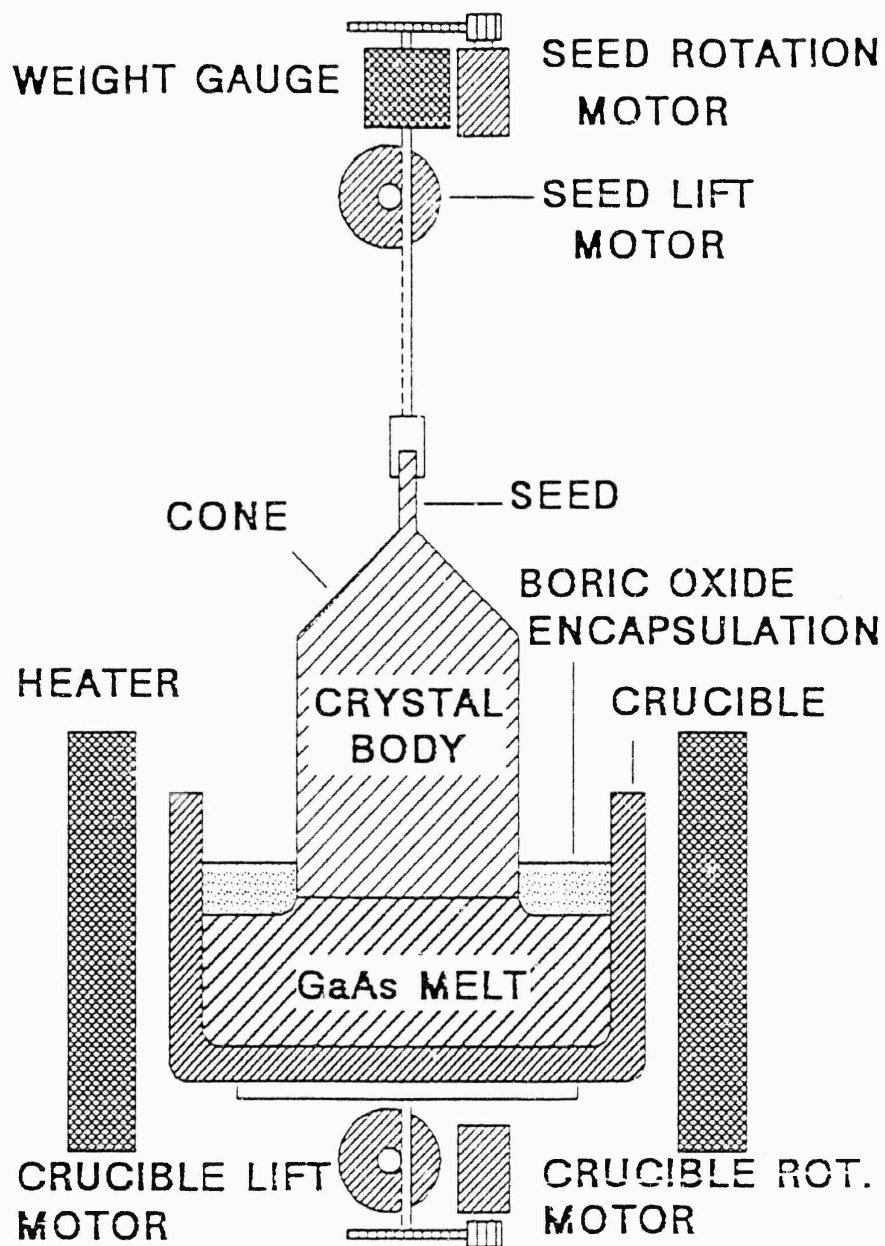Figure 1. A diagram of the Cambridge Instruments puller including the analog and digital control consoles.

Figure 2. A diagram of the Liquid Encapsulated Czochralski puller.
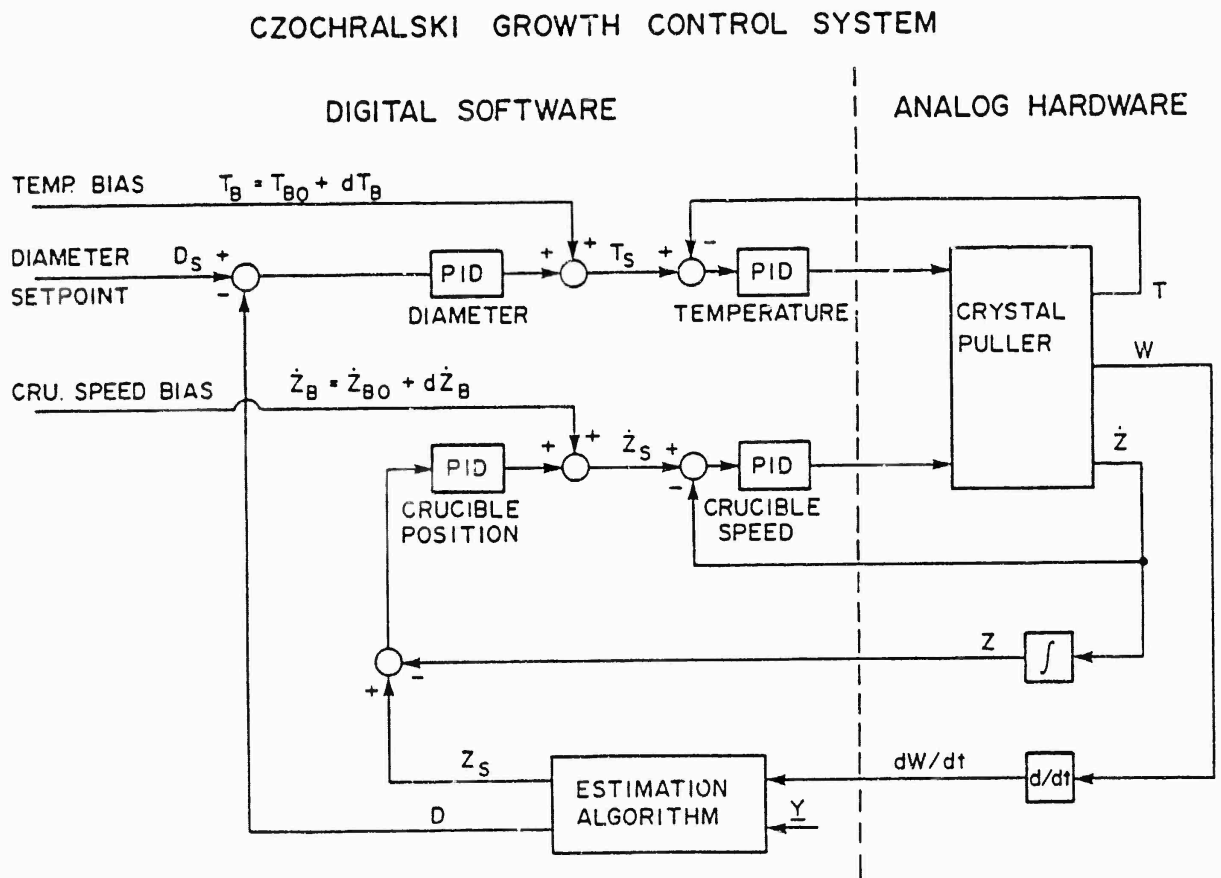
CZOCHRALSKI GROWTH CONTROL SYSTEM

Figure 3.   A simplified diagram of the digital control system. Note: right of the vertical dashed line analog hardware, left of the line digital software.
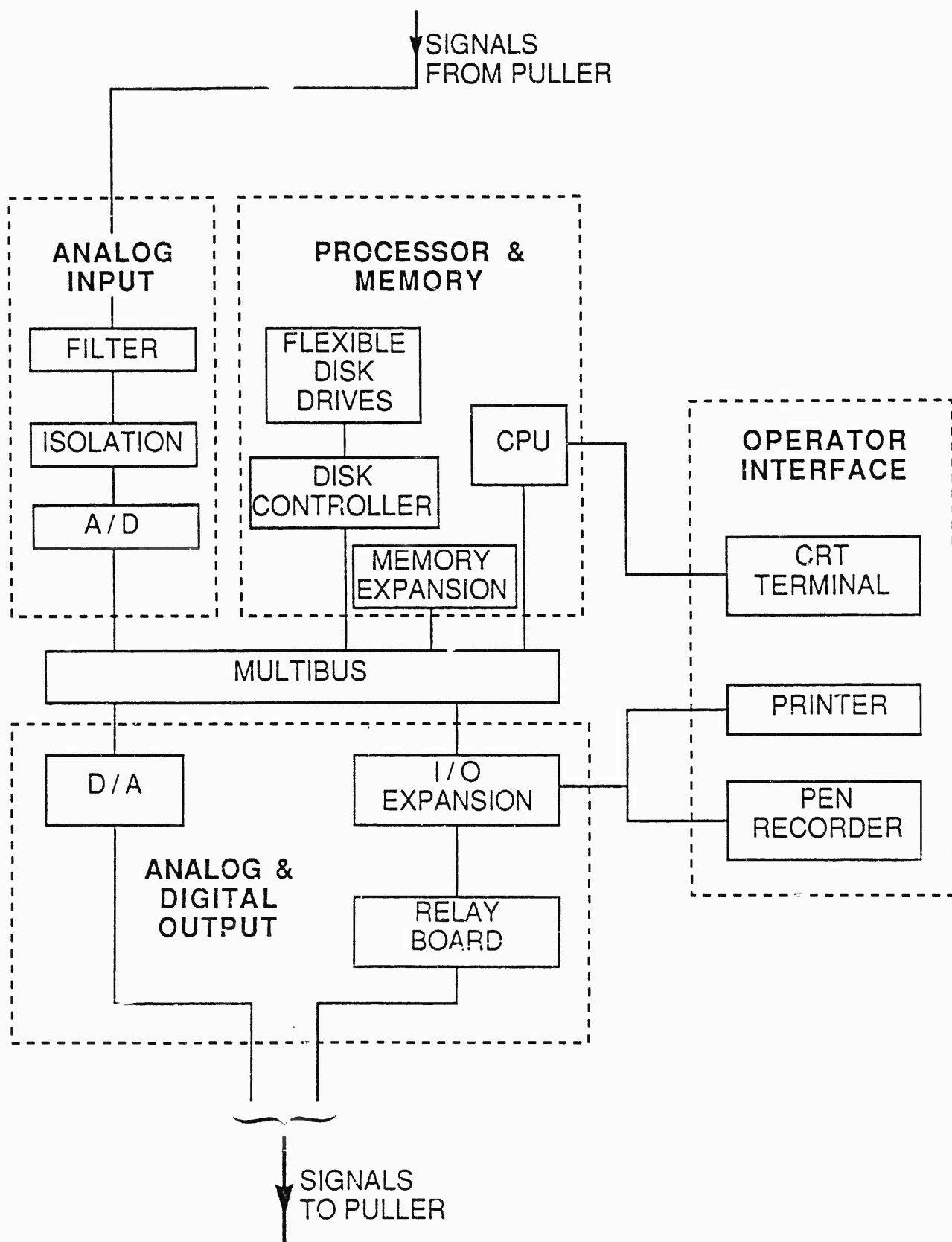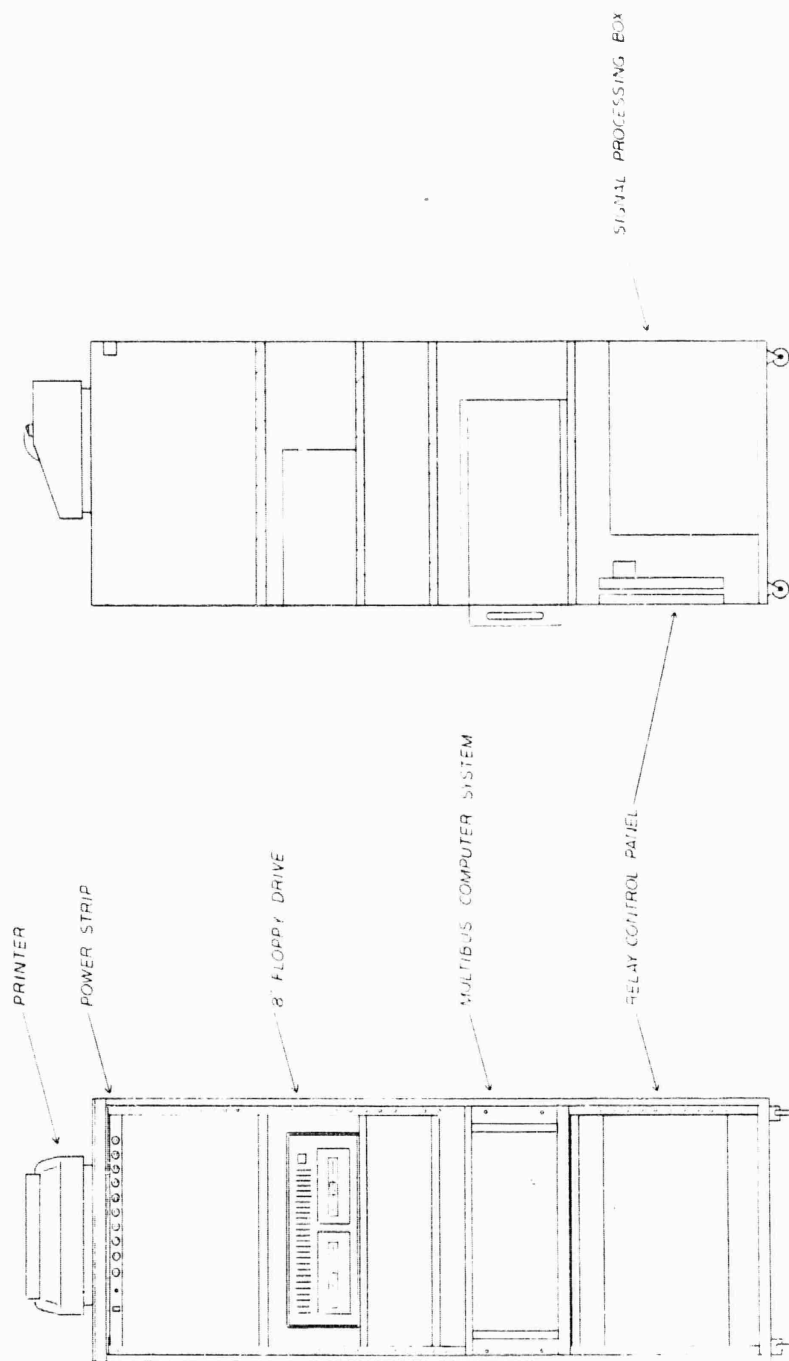
Figure 4   A diagram of the ASU digital control console.

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PRINTER

POWER STRIP

8" FLOPPY DRIVE

MULTIBUS COMPUTER SYSTEM

RELAY CONTROL PANEL

SIGNAL PROCESSING BOX

FRONT

SIDE

Figure 5.   Digital Console Layout.
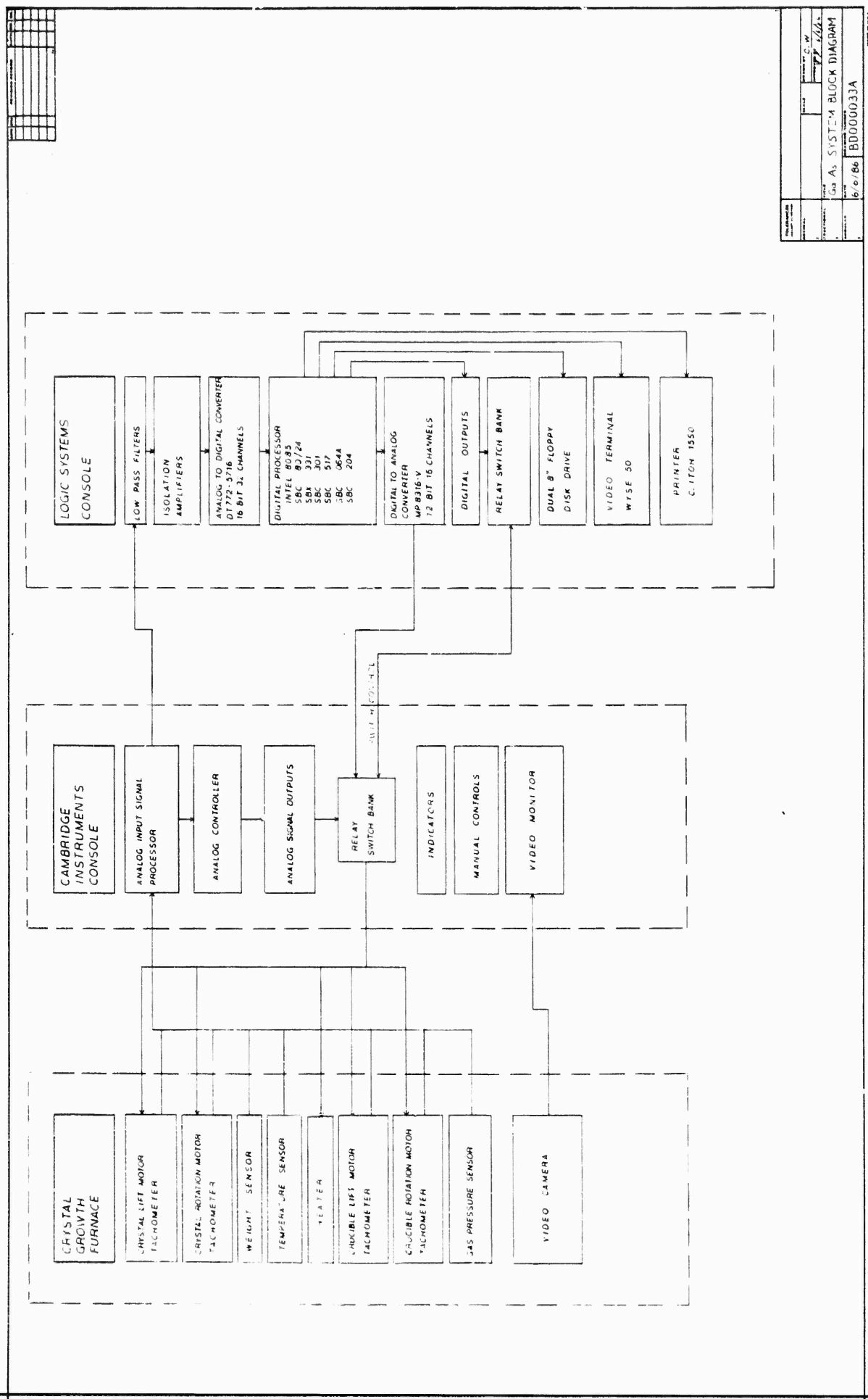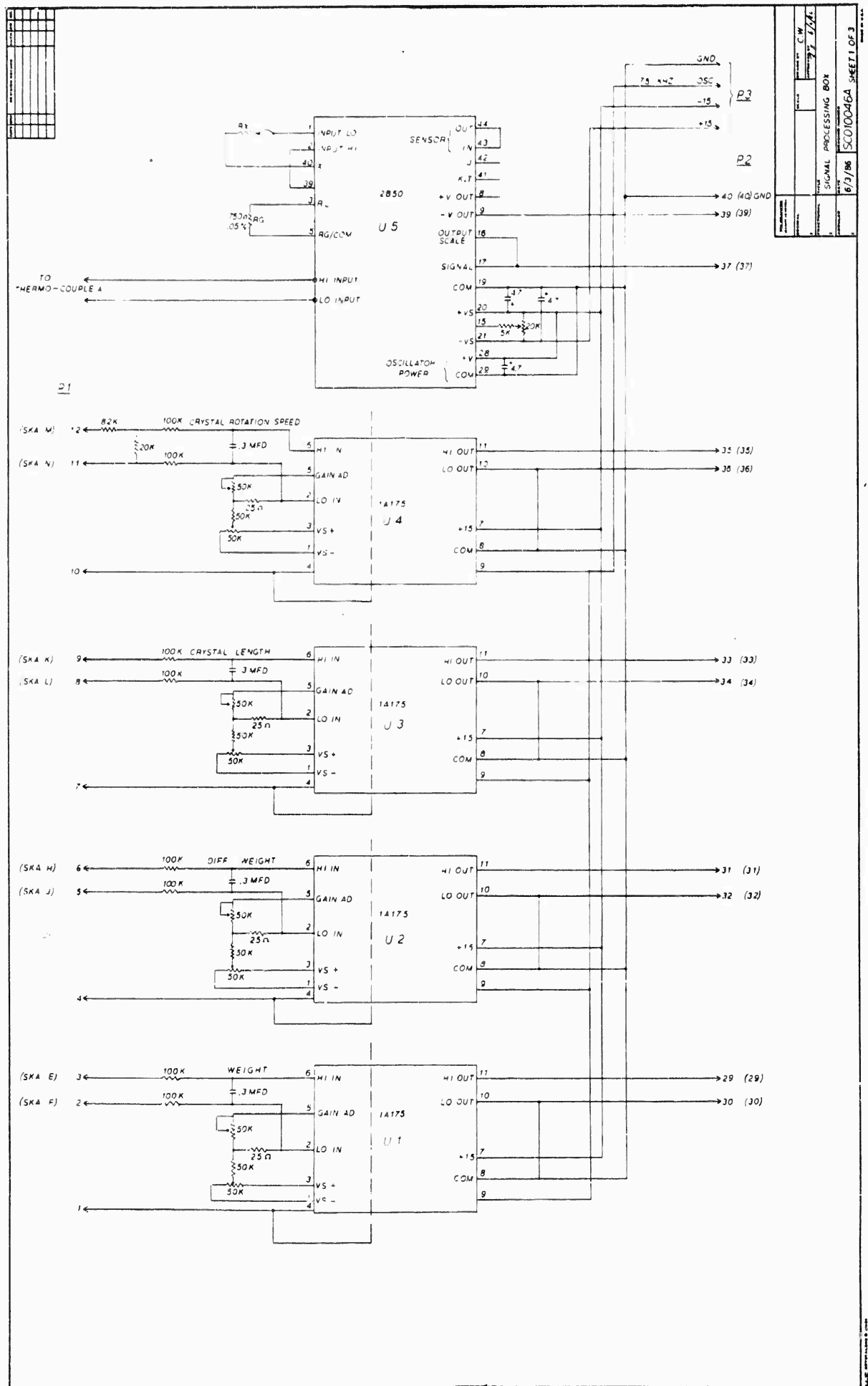
Figure 6. GaAs System Block Diagram.

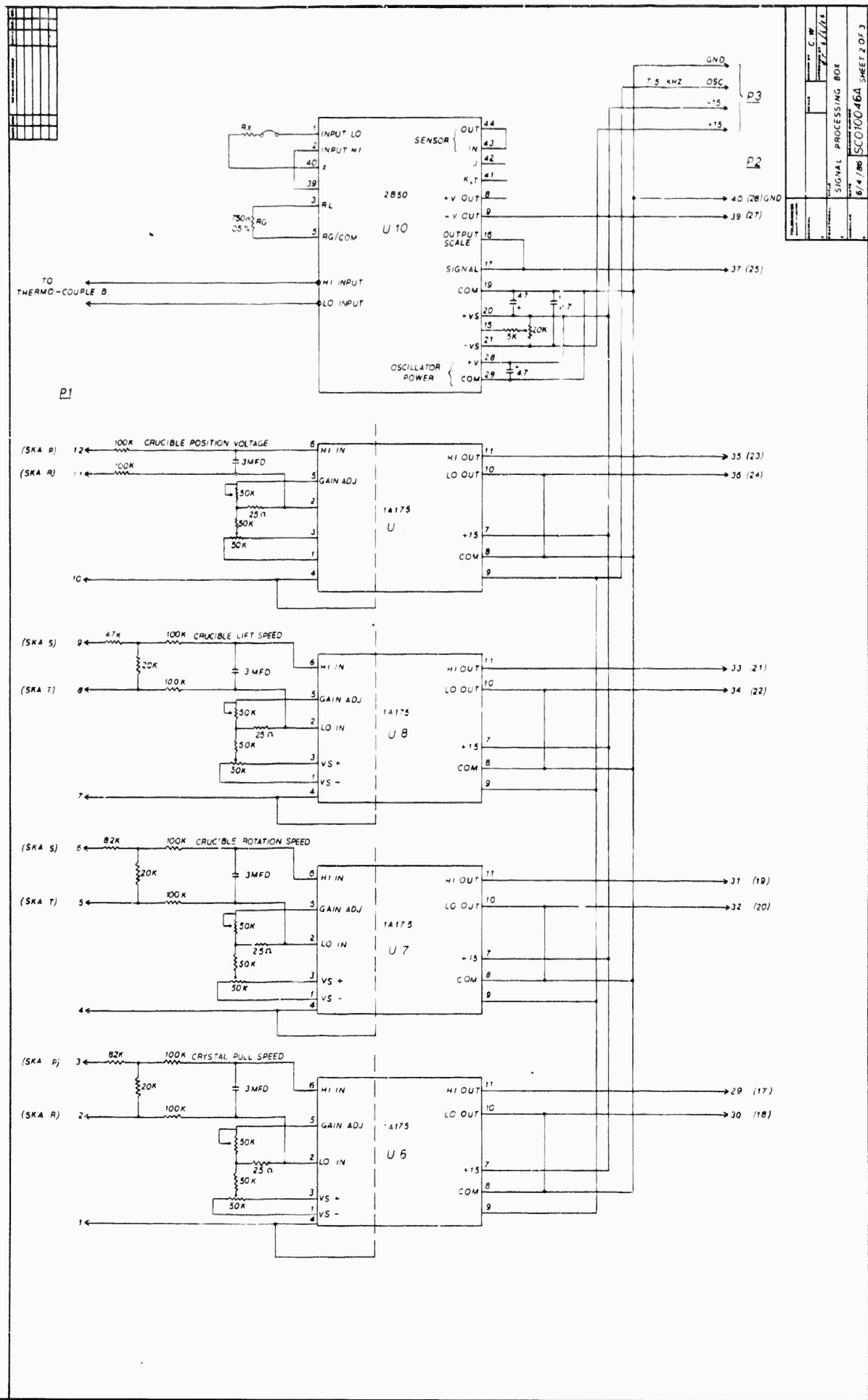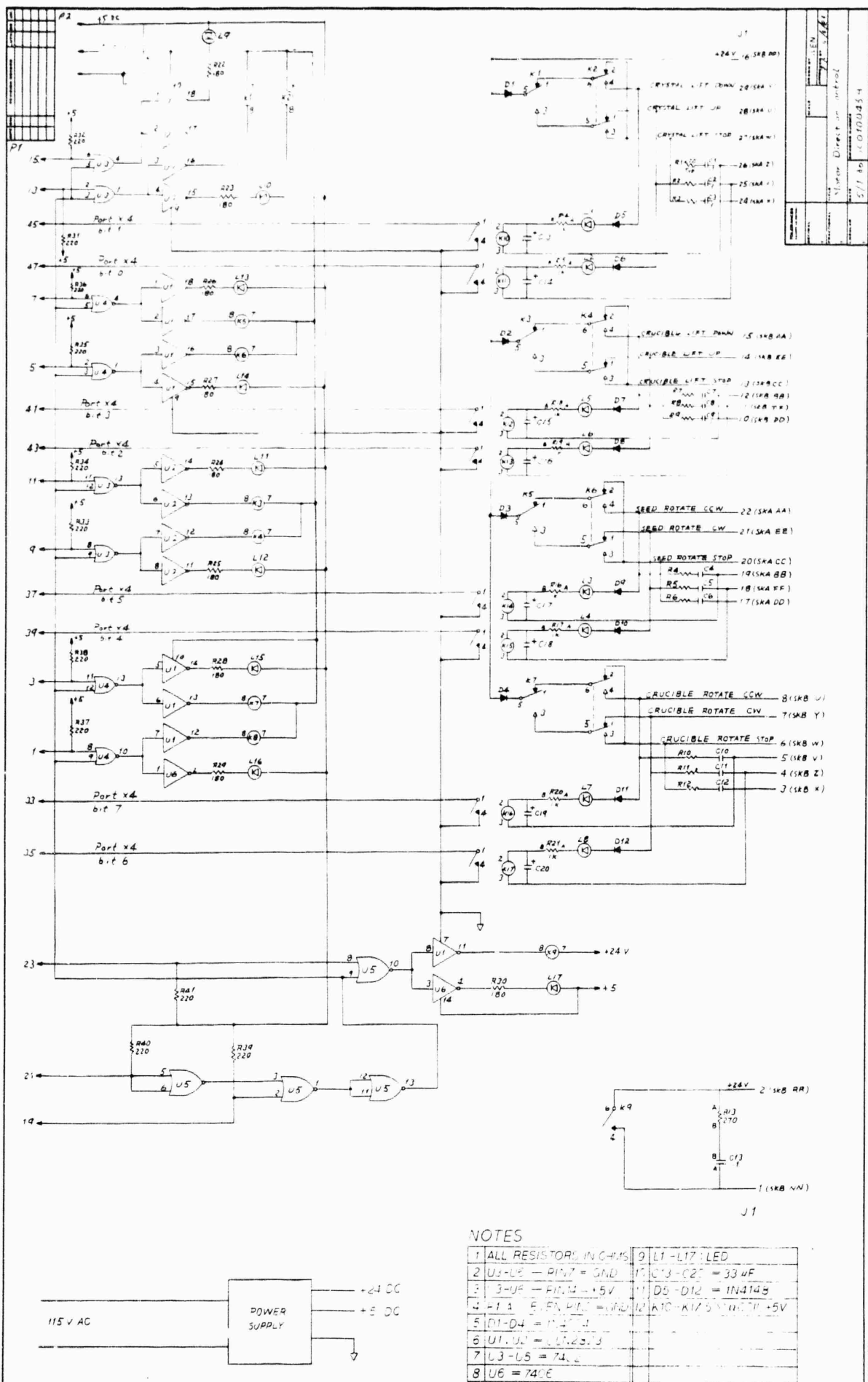Figure 7. Signal Processing Box, Board 1.

Figure 8.   Signal Processing Box, Board 2.

Figure 10. Motor Control Board.